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We present an experimental characterization of the amplification of sub-nanosecond duration laser pulses at a wavelength of 1538 nm in short custom-made Er:Yb phosphate glass fibers with different core diameters. The fibers vary in their diameter from 100 µm (highly multi-mode) down to 12 µm (single-mode). The peak power, energy per pulse, and the spectral shape of the amplified signal are presented. With our input pulses, the measurements show that the large core diameter fibers do not increase the amplification of the 1538 nm signal. We believe this is due to the high re-absorption of the Er^{3+} ions in the phosphate fiber. The optimal fiber geometry was found to be 20 µm core diameter and 14 cm length. The maximum peak power is 8.25 kW, corresponding to a net gain of 10.9 dB, with a pulse duration of 0.7 ns and a repetition rate of 40 kHz.

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In recent years, we have witnessed a significant increase in the need for laser sources having short pulse duration, high repetition rate, and a compact footprint in the eye-safe 1.5 μm region. Applications demanding these laser sources range from Light Detection and Ranging (LIDAR) to remote sensing. This demand drives the research for high-gain and compact fiber amplifiers in the eye-safe spectral range.

Phosphate glass fibers are a great and interesting candidate for these applications due to their excellent properties, such as the ability to achieve a very high concentration of rare-earth ions (e.g. Er^{3+}, Yb^{3+}, and Nd^{3+}) and good energy transfer efficiency in co-doped systems such as Er:Yb [1–4]. Indeed, employing high dopant concentrations and using a weak power seed signal, it is possible to achieve very high gain in a short segment of fiber (typically a few centimeters long) [5]. On the one hand, Erbium-doped silica fibers can typically achieve a gain of 2-3 dB/m, while Er-doped phosphate fibers can reach 200-300 dB/m [6]. On the other hand, Er:Yb co-doped phosphate fibers (EYPHFs) allowed reaching a gain of 500 dB/m for a -30 dBm Continuous Wave (CW) input [7]. In addition, nonlinearities such as stimulated Brillouin scattering and stimulated Raman scattering become increasingly dominant with the length of the fiber, thus limiting the operation in standard active silica glass fibers which have typical lengths of a few meters [8]. The shortening of the EYPHF to lengths of few centimeters significantly reduces the influence of the nonlinearities [9].

These properties enable the integration of a co-doped EYPHF with various core diameters and lengths in a Master Oscillator Power Amplifier (MOPA) configuration. Consequently, high peak power while using a wide range of pulse durations and repetition rates can be obtained. Wei Shi et al. achieved a peak power of 1.2 kW with a fiber of 25/400 μm for a repetition rate of 8 kHz, a wavelength of the seed laser of 1530 nm and a pulse duration of 105 ns [10,11]. In 2008 Pavel Polynkin et al. used a core diameter of 25 μm in order to achieve an energy per pulse of 215 μJ with a low repetition rate of 0.605 kHz and pulse width of 22 ns corresponding to a peak power of 9.18 kW [12]. For shorter pulses, M. Leigh et al. used a four-stage MOPA to achieve a peak power of 51.5 kW with a signal of 1550.67 nm, a repetition rate of 5 kHz and pulse width of 2-3 ns (they used a 12 cm-long section of EYPHF with a fiber of 12/125 μm) [13]. However, no research has examined the effect of the diameter and length of the phosphate fiber on the amplifier performance.

In this paper, we systematically characterize the effect of diameter and length on the net gain of an EYPHF amplifier, this might shed more light on the performance of these amplifiers for pulsed lasers. These experiments were performed with custom-made EYPHFs with different core to cladding diameter ratios. To the best of our knowledge, this is the first example of an active phosphate fiber with cladding obtained by an extrusion process. The EYPHFs were designed and drawn by preform drawing, with the preform being obtained by the rod-in-tube technique. Core and cladding glasses were synthesized by melting a powder batch of high purity chemicals (99+%) inside an alumina crucible at a temperature of around 1400 °C for 1 h under a controlled atmosphere (dry air, water content < 3 ppm). The core of the different EYPHFs was doped with 3.86 × 10^{20} cm^{-3} of Yb^{3+} and 1.93 × 10^{20} cm^{-3} of Er^{3+} (Er:Yb ratio of 1:2). The core glass was then cast into a cylindrical mold to form a rod, while the undoped cladding glass was shaped into a tube by rotational casting method (fibers #1-3 – see Table 1) or extrusion technique (fibers #4-5 – see Table 1). The extrusion

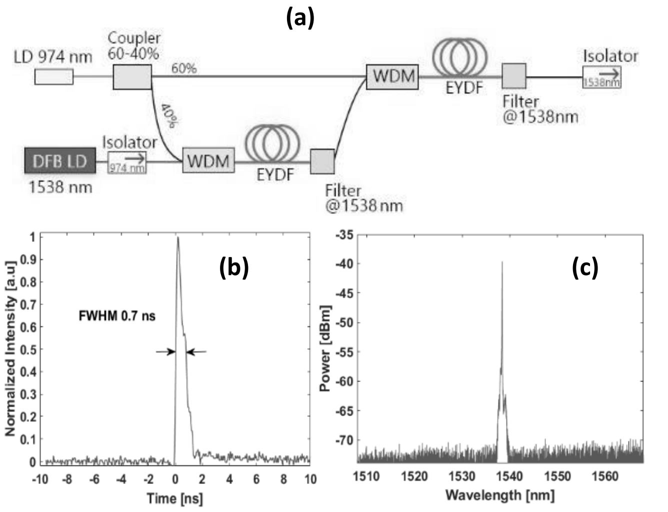

Fig. 1. (a) The seed pulsed laser scheme, (b) the temporal shape of the amplified pulse with 0.7 ns in full-width-half-maximum (FWHM), and (c) the spectrum of the amplified pulse.

has been successfully employed for the manufacturing of tellurite and germanate glass preforms [14-15], but very little literature is available on the extrusion of phosphate glasses [16]. In addition, it is worthwhile highlighting that extrusion is a novel technique to fabricate EYPHF preforms.

The EYPHFs of different sizes were obtained by drawing the core/cladding preform using a drawing tower developed in-house, whose furnace consists of a graphite ring heated by induction operating at 248 kHz and delivering 170 W to reach the drawing temperature (SAET, Torino, Italy). The attenuation losses of the fibers were measured with the cut-back technique for a wavelength of 1300 nm. Besides, fibers #1-3 have relatively large core diameters, consequently, these fibers are highly multi-mode (V number of 22.46, 17.52 and 11.23 respectively). The last two fibers have much smaller core diameters so their V-number is significantly smaller (4.85 and 2.03). Moreover, fiber #5 is a single-mode fiber. The relevant parameters of the fibers are summarized in Table 1.

The scheme of the seed laser and the spectral/temporal shape of the seed pulses are shown in Fig. 1. We started with a fiber-coupled semiconductor CW single-mode laser diode with a central wavelength of 1538 nm and average power of ~20 mW (Alcatel-Lucent A1905LMI distributed feedback (DFB) laser diode). This diode was gain-switched to provide 1 ns pulse duration. The laser is spliced to a Wavelength Division Multiplexing (WDM) and amplified with two stages of amplification. After each stage, the Amplified Spontaneous Emission (ASE) is filtered out with a filter (bandwidth of 100 GHz) centered at 1538 nm (see Fig. 1b for seed spectrum). The pump power of 700 mW at 974 nm (Ⅱ-Ⅵ CM97-770-74) is divided through a splitter with a split ratio of 40/60% between the first and the second stage, respectively. The final average output power was 20 mW, with a pulse duration of 0.7 ns (see Fig. 1c) and a repetition rate of 40 kHz which gives a calculated energy per pulse of 0.5 µJ. For the Gaussian-like shaped output pulse at 1538 nm, the calculated peak power is 0.67 kW [17].

Table 1. Main parameters of the fabricated EYPHFs.

Fiber	Core/Clad diameters [µm]	n_{Core}	n_{Clad}	NA	Att. Losses in 1300 nm [dB/cm]
1	100/230	1.5661	1.5620	0.11	0.036
2	78/178	1.5661	1.5620	0.11	0.036
3	50/125	1.5661	1.5620	0.11	0.036
4	20/125	1.5681	1.5636	0.12	0.022
5	12/125	1.5661	1.5639	0.08	0.020

The experimental phosphate fiber amplification setup is shown in Fig. 2. The single-mode seed laser output and a multi-mode fiber-coupled pump laser diode (central wavelength of 915 nm – JDSU L4-9891510, it is possible to use this pumping wavelength due to the Ytterbium doping which absorbs in this spectrum) were coupled with a pump combiner (8/125 µm, 0.14/0.46 NA DCF) and butt-coupled to various EYPHF segments which were held straight and served as the phosphate amplification stage. A second narrow-band pump laser diode with a wavelength of 976 nm (BWT K976AA5RN-60.00W) was coupled to the rear facet of the EYPHF using two aspheric lenses with focal lengths of 20 and 40 mm which image a spot size of $\sim 60\ \mu m$ on the facet (L1 and L2 in Fig. 2, respectively). It should be mentioned that the interface air-clad in all fibers results in a very big NA, therefore there are no pump coupling issues in both facets. The amplified seed laser is reflected by a dichroic mirror towards the power meter (through a filter that blocks both the residual pump and the 1 μm spontaneous emission). In addition, the spectrum and the pulse shape of the output were measured with an optical spectrum analyzer (Yokogawa AQ6370D) and a fast InGaAs photodiode with a rise time of 70 ps (Thorlabs DET08C). Furthermore, we expected that the optimum length of the highly multi-mode fibers will be much shorter than those with the low V-number. Thus, we present and discuss the results separately for the large core fibers (#1-3) and the small core fibers (#4, 5). In order to check the net gain in the large core fibers, we have tested different fiber lengths with a maximum of 10 cm using a pump power of 9 W (5.5 W of pump 1 and 3.5 W of pump 2). Indeed, a relatively large pump absorption was observed; therefore, we present and discuss here only lengths up to 5 cm. The laser output power as a function of pump power is shown in Fig. 3a for different lengths of fiber #3. Figure 3b presents the average output power of the amplified seed after passing through fibers #1-3 with the same

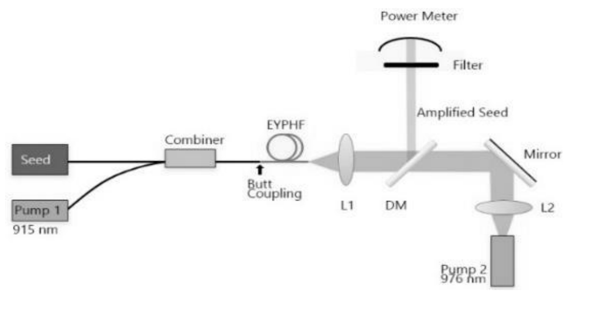

Fig. 2. The experimental setup. EYPHF- Er:Yb phosphate fiber, DM – dichroic mirror, L1 and L2- aspheric lenses.

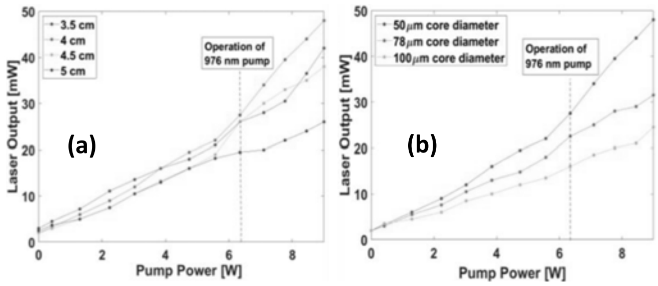

Fig. 3. (a) Average output power with different lengths of fiber #3. (b) Average output power of the amplified seed from EYPHFs #1-3 with length of 4 cm. The points represent actual measurements (connecting lines are just for clarity).

optimum fiber length of 4 cm. The reason why the optimal length for fibers #1-3 is the same might be ascribed to the roughly equal core/clad ratio of areas in all the three fibers (~0.19 for fibers #1-2 and 0.16 for fiber #3). As evident, the 50 μm core exhibits the highest average power of 48 mW. In comparison, the output of the 100 μm core is 24.5 mW and for the 78 μm the output is 31.5 mW. This result clearly shows that reducing the core size provides higher gain and output power. We believe this result has a few reasons. First, the high doping concentration which leads to the high absorption of both the signal and pump in the large core fibers. This is typical to Er^{3+} since absorption and emission peaks are in the same spectral region. The high doping concentration may also lead to the process of cooperative up-conversion between the Er^{3+} ions which finally reduces the population of the Er^{3+}:$^4I_{13/2}$ energy level and impairs the lasing power. Nevertheless, it should be noted that in phosphate fibers this process is relatively weak [3]. Besides, the seed power might be too weak to saturate the amplifiers. The ASE process is another factor that limits the output power of the pulsed amplifiers. At 40 kHz repetition rate the time between pulses is 25 μs, which is significantly shorter than the lifetime of Er^{3+}:$^4I_{13/2}$ energy level (the average measured lifetime of the core of our fibers is 6.3 ms). Therefore, ASE exists but it is significantly reduced compared to low repetition rates. Finally, no preleasing was observed with the optical spectrum analyzer, hence, it also cannot be the reason for the low amplification. It should be noted that the absolute output power was limited due to the limited pump power (9 W; above that damage to the input facet was observed). In Fig. 4 we show the optimal amplifier performance among fibers #1-3. Figure 4 presents the peak power of the output pulse as a function of pump power. A maximum amplification of 3.8 dB was achieved with the fiber #3 and 4 cm length. In comparison, with 50 μm and 5 cm we obtained only 1.14 dB. As evident, with large core diameters, the amplification is very sensitive to small changes in the length. This may be due to reabsorption in weakly pumped regions, in addition to the reasons stated above. The spectrum measured with a resolution of 0.02 nm is shown in the inset of Fig. 4 and shows that the laser peak is much higher than the ASE (~40 dB). This justified using the measured average output power in order to calculate the energy per pulse and the peak power. The calculation showed an energy per pulse of 1.2 μJ with a peak power of 1.6 kW.

In the experiments with the small core diameter fibers (#4 and #5), only the backward pump laser diode was operated. Adding the forward pump diode had only a minor effect on the amplification. In order to prevent parasitic CW lasing that appeared already at low pump powers, we angled cleaved one of the facets of the fiber to prevent feedback into the doped core. With the small core diameter fibers, longer fibers (compared to fibers #1-3) showed higher amplification. Figure 5 presents the performance of the optimal fiber length with fibers #4 and #5 in terms of peak pulse power. Fiber #5 (12 μm core) showed an increase in output power with fiber length until an optimum fiber length of 16 cm was obtained. With this length, the average output power reached 147 mW, equivalent to an energy per pulse of 3.67 μJ and peak power of 4.93 kW. With fiber #4 (20 μm core) a significantly higher amplification was achieved with an optimum length of 14 cm. The average power reached 246 mW, the energy per pulse 6.15 μJ, and the peak power 8.25 kW. In terms of net gain, the amplification with fibers #4 and #5 is 10.9 dB and 8.67 dB, respectively, which is much higher than the amplification that has been achieved with the large core diameter fibers. Note that with higher pumping power, the amplification could be even higher, since Fig. 5a shows no saturation at the maximum pump power (limited by fiber facet damage). As evident, the optimal lengths with fibers #4 and #5 are about four times longer than with fibers #1-3, yet considerably shorter than those of silica glass amplifiers. However, the decrease in the core diameter leads to a significant increase in the amplification, without the appearance of nonlinear processes. As the core size is reduced, the pump absorption reduces as well (double-clad pumping), and the absorption is more homogeneous along with the fiber. This may be the reason for reduced losses due to reabsorption. The inset of Fig. 5 shows the spectrum of the output pulses from fiber #4 with a length of 14 cm. No parasitic lasing or significant ASE were measured, the difference between the laser peak and the ASE is more than 50 dB.

The output beam quality in the small core diameter cases, which showed the best amplification performance, was measured using the knife-edge technique and calculating the M^2 parameter. The measured value for fiber #5 is ~1.1 (Fig. 6a), very close to a perfect single-mode beam. This result is in good correspondence with the V-number of this fiber which is 2.03. The measured M^2 value for fiber #4 is ~1.2 (Fig. 6b), indicating good beam quality even though the V-number of the fiber is higher than 2.405.

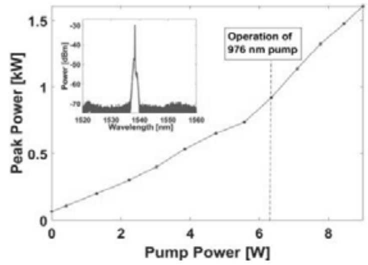

Fig. 4. Peak power of the optimal large core fiber (50 μm core diameter and 4 cm length). Inset: the spectrum.

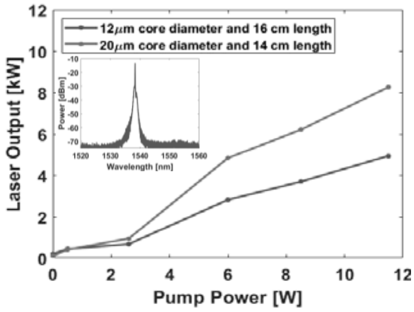

Fig. 5. Peak power of the amplified seed laser with the optimum length of fibers #4 and #5. Inset: spectrum of the amplified seed laser with fiber #4 and 14 cm length.

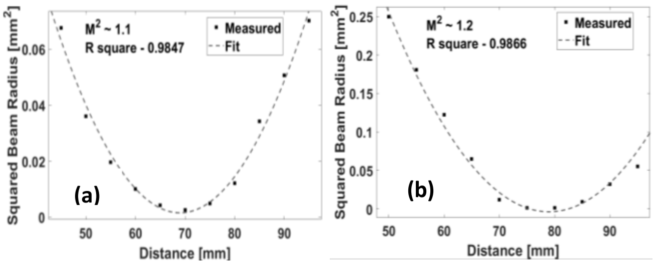

Fig. 6. (a) Beam quality measurements of fiber #5. (b) Beam quality measurements of fiber #4.

This can be explained by the relatively short length of the fiber amplifier, which maintains the single-mode seed laser beam quality, a result of much higher amplification of the fundamental mode compared to the others [12].

Finally, Fig. 7 shows the total amplification as a function of the fiber core diameter, where the fiber length was optimal in each case (4 cm for fibers #1-3, 14 cm for fiber #4 and 16 cm for fiber #5). As can be seen, the highest amplification is obtained with the 20 μm core fiber. It may be possible to obtain even higher amplification by using core diameters which are slightly smaller or larger than 20 μm.

In conclusion, we have characterized the amplification of sub-nanosecond 1538 nm pulses at a high repetition rate with five custom-made EYPHFs with different core diameters. In each case, the optimal fiber length was determined and the net gain was measured. We have found that the large core diameter fibers do not result in higher gain. This may be attributed to the high (and inhomogeneous) pump absorption in the case of large core diameters in addition to the possibility of cooperative up-conversion process in the system. It is also possible that the seed input power was too weak in order to saturate the large core amplifiers. In terms of amplification, the optimal amplifier was found to be the 20 μm core diameter fiber with a length of 14 cm. With these parameters, the peak power reached 8.25 kW and the energy per pulse was 6.15 μJ, which is equivalent to amplification of 10.9 dB. This amplification, combined with good beam quality ($M^2 \sim 1.2$), can lead to a relatively compact and robust amplifier. Moreover, the good performance exhibited by phosphate fibers whose clad preform was manufactured by the extrusion process paves the way toward the realization of phosphate fiber amplifiers with more complex structures that can lead to a more efficient optical amplification.

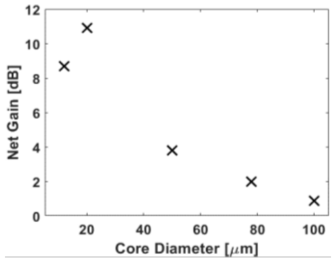

Fig. 7. Net gain vs. core diameter when adopting the optimum fiber length.

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Disclosures. The authors declare no conflicts of interest.

References

1. N. G. Boetti, D. Pugliese, E. Ceci-Ginistrelli, J. Lousteau, D. Janner, and D. Milanese, Appl. Sci. **7**, 1295 (2017).
2. L. Li, M. M. Morrell, T. Qiu, V. L. Temyanko, A. Schülzgen, A. Mafi, D. Kouznetsov, J. V. Moloney, T. Luo, S. Jiang, and N. Peyghambarian, Appl. Phys. Lett. **85**, 2721 (2004).
3. B.-C. Hwang, S. Jiang, T. Luo, J. Watson, G. Sorbello, and N. Peyghambarian, J. Opt. Soc. Am. B **17**, 833 (2000).
4. C. Strohhöfer and A. Polman, J. Appl. Phys. **90**, 4314 (2001).
5. B- C. Hwang, S. Jiang, T. Luo, K. Seneschal, G. Sorbello, M. Morrell, F. Smektala, S. Honkanen, J. Lucas and N. Peyghambarian, IEEE Photonics Technol. Lett. **13**, 197 (2001).
6. M. R. Lange, E. Bryant, M. J. Myers, and J. D. Myers, National Fiber Optic Engineering Conference (NFOEC) paper **126** (2003).
7. Y. Hu, S. Jiang, T. Luo, K. Seneschal, M. Morrell, F. Smektala, S. Honkanen, J. Lucas, and N. Peyghambarian, IEEE Photonics Technol. Lett. **13,** 657 (2001).
8. D. J. Richardson, J. Nilsson, and W. A. Clarkson, J. Opt. Soc. Am. B **27**, B63 (2010).
9. E. Petersen, W. Shi, A. Chavez-Pirson, and N. Peyghambarian, Appl. Opt. **51**, 531 (2012).
10. W. Shi, E. B. Petersen, M. Leigh, J. Zong, Z. Yao, A. Chavez-Pirson, and N. Peyghambarian, Opt. Express **17,** 8237 (2009).
11. W. Shi, E. B. Petersen, Z. Yao, D. T. Nguyen, J. Zong, M. A. Stephen, A. Chavez-Pirson, and N. Peyghambarian, Opt. Lett. **35,** 2418 (2010).
12. P. Polynkin, N. Peyghambarian, and J. Moloney, Appl. Phys. Lett. **92,** 061115 (2008).
13. M. Leigh, W. Shi, J. Zong, Z. Yao, S. Jiang, and N. Peyghambarian, Appl. Phys. Lett. **92,** 181108 (2008).
14. H. Ebendorff-Heidepriem and T. M. Monro, Opt. Express **15**, 15086 (2007).
15. J. Lousteau, H. Bookey, X. Jiang, C. Hill, A. Kar, and A. Jha. 9th International Conference on Transparent Optical Networks **2**, 305 (2007).
16. D. Gallichi-Nottiani, D. Pugliese, N. G. Boetti, D. Milanese, and D. Janner, Int. J. Appl. Glass Sci. **in press**, 10.1111/ijag.14652.
17. W. Shi, E. B. Petersen, M. Leigh, J. Zong, Z. Yao, A. Chavez-Pirson, and N. Peyghambarian, Fiber Lasers VI Technol. Syst. Appl. **7195,** 71951H (2009).